

# Interaction of self-trapped beams in high index glass

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**Abstract:** We observe attraction, repulsion and energy exchange between two self-trapped beams in a heavy-metal-oxide glass exhibiting a Kerr-like response with multiphoton absorption. The coherent interaction between spatial solitons is controlled by their relative phase and modeled by a nonlinear dissipative Schrödinger equation.

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## References and links

1. R. Y. Chiao, E. Garmire, and C. H. Townes, "Self-trapping of optical beams," *Phys. Rev. Lett.* **13**(15), 479–482 (1964).
2. P. L. Kelley, "Self-focusing of optical beams," *Phys. Rev. Lett.* **15**(26), 1005–1008 (1965).
3. A. W. Snyder, D. J. Mitchell, L. Poladian, and F. Ladouceur, "Self-induced optical fibers: spatial solitary waves," *Opt. Lett.* **16**(1), 21–23 (1991).
4. N. N. Akhmediev, and A. Ankiewicz, *Solitons: Nonlinear Pulses and Beams* (Chapman Hall, London, 1997).
5. G. I. Stegeman, and M. Segev, "Optical spatial solitons and their interactions: Universality and diversity," *Science* **286**(5444), 1518–1523 (1999).
6. Y. S. Kivshar, and G. P. Agrawal, *Optical Solitons* (Academic Press, San Diego, 2003).
7. C. Conti, and G. Assanto, "Nonlinear Optics Applications: Bright Spatial Solitons", in *Encyclopaedia of Modern Optics*, eds. R. D. Guenther, D. G. Steel and L. Bayvel, vol. 5 (Elsevier, Oxford, 2004).
8. M. Shalaby, and A. Barthelemy, "Experimental spatial soliton trapping and switching," *Opt. Lett.* **16**(19), 1472 (1991).
9. P. V. Mamyshev, A. Villeneuve, G. I. Stegeman, and J. S. Aitchison, "Steerable optical waveguides formed by bright spatial solitons in AlGaAs," *Electron. Lett.* **30**(9), 726 (1994).
10. W. E. Torruellas, G. Assanto, B. L. Lawrence, R. A. Fuerst, and G. I. Stegeman, "All-optical switching by spatial walk-off compensation and solitary-wave locking," *Appl. Phys. Lett.* **68**(11), 1449–1451 (1996).
11. G. Leo, and G. Assanto, "Phase- and polarization-insensitive all-optical switching by self-guiding in quadratic media," *Opt. Lett.* **22**(18), 1391–1393 (1997).
12. L. Friedrich, G. I. Stegeman, P. Millar, C. J. Hamilton, and J. S. Aitchison, "Dynamic, electronically controlled angle steering of spatial solitons in AlGaAs slab waveguides," *Opt. Lett.* **23**(18), 1438–1440 (1998).
13. M. Peccianti, C. Conti, G. Assanto, A. De Luca, and C. Umeton, "All Optical Switching and Logic Gating with Spatial Solitons in Liquid Crystals," *Appl. Phys. Lett.* **81**(18), 3335–3337 (2002).
14. G. Assanto, and M. Peccianti, "Routing light at will," *J. Nonlinear Opt. Phys. Mater.* **16**(1), 37–48 (2007).
15. J. S. Aitchison, A. M. Weiner, Y. Silberberg, D. E. Leaird, M. K. Oliver, J. L. Jackel, and P. W. E. Smith, "Experimental observation of spatial soliton interactions," *Opt. Lett.* **16**(1), 15–17 (1991).
16. M. Shalaby, F. Reynaud, and A. Barthelemy, "Experimental observation of spatial soliton interactions with a  $\pi/2$  relative phase difference," *Opt. Lett.* **17**(11), 778–780 (1992).
17. J. U. Kang, G. I. Stegeman, and J. S. Aitchison, "One-dimensional spatial soliton dragging, trapping, and all-optical switching in AlGaAs waveguides," *Opt. Lett.* **21**(3), 189–191 (1996).
18. V. Tikhonenko V, J. Christou, and B. Luther-Davies, "Three dimensional bright spatial soliton collision and fusion in a saturable Nonlinear Medium," *Phys. Rev. Lett.* **76**(15), 2698–2701 (1996).
19. G. Leo, G. Assanto, and W. E. Torruellas, "Intensity-controlled interactions between vectorial spatial solitary waves in quadratic nonlinear media," *Opt. Lett.* **22**(1), 7–9 (1997).
20. B. Costantini, C. De Angelis, A. Barthelemy, A. Laureti Palma, and G. Assanto, "Polarization multiplexed  $\chi^{(2)}$  solitary waves interactions," *Opt. Lett.* **22**(18), 1376–1378 (1997).

21. Y. Baek, R. Schiek, G. I. Stegeman, I. Baumann, and W. Sohler, "Interactions between one-dimensional quadratic solitons," *Opt. Lett.* **22**(20), 1550–1552 (1997).
22. M. Peccianti, K. A. Brzdkiewicz, and G. Assanto, "Nonlocal spatial soliton interactions in nematic liquid crystals," *Opt. Lett.* **27**(16), 1460–1462 (2002).
23. C. Rotschild, B. Alfassi, O. Cohen, and M. Segev, "Long range interactions between spatial solitons," *Nat. Phys.* **2**(11), 769–774 (2006).
24. A. Dubietis, E. Gaizauskas, G. Tamosauskas, and P. Di Trapani, "Light filaments without self-channeling," *Phys. Rev. Lett.* **92**(25), 253903 (2004).
25. E. A. Ultanir, G. I. Stegeman, C. H. Lange, and F. Lederer, "Coherent interactions of dissipative spatial solitons," *Opt. Lett.* **29**(3), 283–285 (2004).
26. T.-S. Ku, M.-F. Shih, A. A. Sukhorukov, and Y. S. Kivshar, "Coherence controlled soliton interactions," *Phys. Rev. Lett.* **94**(6), 063904 (2005).
27. A. Fratalocchi, A. Piccardi, M. Peccianti, and G. Assanto, "Nonlinearly controlled angular momentum of soliton clusters," *Opt. Lett.* **32**(11), 1447–1449 (2007).
28. J. Gonzalo, H. Fernandez, J. Solis, D. Munoz-Martin, J. M. Fernandez-Navarro, C. N. Afonso, and J. L. G. Fierro, "Enhanced nonlinear optical properties of oxygen deficient lead-niobium-germanate film glasses," *Appl. Phys. Lett.* **90**(25), 251907 (2007).
29. A. Pasquazi, S. Stivala, G. Assanto, J. Gonzalo, J. Solis, and C. N. Afonso, "Near-infrared spatial solitons in heavy metal oxide glasses," *Opt. Lett.* **32**(15), 2103–2105 (2007).
30. A. Pasquazi, S. Stivala, G. Assanto, J. Gonzalo, and J. Solis, "Transverse nonlinear optics in heavy metal oxide glass," *Phys. Rev. A* **77**(4), 043808 (2008).
31. E. V. Vanin, A. I. Korytin, A. M. Sergeev, D. Anderson, M. Lisak, and L. Vázquez, "Dissipative optical solitons," *Phys. Rev. A* **49**(4), 2806–2811 (1994).
32. N. Akhmediev, and A. Ankiewicz, *Dissipative Solitons* (Springer, New York, 2005).
33. G. Fibich, and A. L. Gaeta, "Critical power for self-focusing in bulk media and in hollow waveguides," *Opt. Lett.* **25**(5), 335–337 (2000).

## 1. Introduction

The propagation and interaction of self-trapped optical beams or bright spatial solitons have intrigued the scientific community for decades [1–7]. Solitons in more than one transverse dimension undergo catastrophic beam collapse in Kerr media [1,2]; hence, stabilizing mechanisms such as saturation or nonlocality, are required for stable propagation [4–7]. Due to the intrinsic instability of two-dimensional ( $2D + 1$ ) Kerr solitons, several nonlinear materials cannot be employed for their propagation in bulk, despite the growing attention on soliton based all-optical devices [8–14]. In general, glasses with an ultrafast purely Kerr response are in the category of unsuitable materials for  $2D + 1$  solitons and, due to their small nonlinearity, require pulsed excitations with high intensities.

Interactions between solitons have been investigated in various systems [13,15–27]. Hereby, based on the results we recently obtained in high index glasses of the heavy-metal-oxide (HMO) family  $\text{Nb}_2\text{O}_5\text{-PbO-GO}_2$  [28] with the aid of three-photon absorption at wavelengths around 800nm [29,30], we investigate the interaction of two coherent  $2D + 1$  soliton-like beams in such dissipative medium [25,31,32]. By controlling the relative phase of the self-trapped beams excited with picosecond pulses in the first telecom spectral window, we observed repulsion, attraction and energy exchange; the overall transmittance showing the fingerprint of three photon absorption.

## 2. Experimental setup and model

We used single 25 ps pulses produced at 800nm by a 10Hz repetition-rate optical parametric generator. The beam was spatially filtered to the fundamental  $\text{TEM}_{00}$  mode. Polarizing optics and half-wave plates allowed adjusting both peak power (energy) and polarization. Two parallel copropagating beams were obtained in a Mach-Zehnder arrangement and their relative phase was controlled with a tilted thin glass slide. The beams were gently focused to a waist of  $13\mu\text{m}$  on the input facet of a  $25\text{Nb}_2\text{O}_5\text{-}25\text{PbO-}50\text{GeO}_2$  mol% glass sample of thickness 5.75mm, in order to allow a propagation length exceeding four Rayleigh lengths along  $z$ . Images of the output beam were acquired with an infrared enhanced CCD camera through a microscope objective. Dual channel boxcar averager and computer controls were used to filter out the noise as well as undesired pulses of energy outside the prescribed range.

Laser beam propagation in optical dielectrics with a Kerr response and dissipation can be described by a nonlinear Schrödinger equation with a corrective term for three-photon absorption (3PA) [25,29,30]:

$$2ik\partial A_z + \nabla_{\perp}^2 A + \frac{n_2 k^2}{\eta_0} |A|^2 A + ik\beta_3 \left(\frac{n_0}{2\eta_0}\right)^2 |A|^3 A = 0 \quad (1)$$

with  $A = A(x, y, z)$  the slowly varying amplitude of the electric field  $E(x, y, z, t) = \frac{1}{2}A(x, y, z)\exp(ikz - i\omega t) + cc$ ,  $k$  the wavenumber,  $\eta_0$  the vacuum impedance,  $n_0$  the refractive index;  $n_2$  is the Kerr coefficient as in  $n(I) = n_0 + n_2 I$ , with  $I$  the intensity and  $\beta_3$  is the 3PA coefficient as defined by  $\partial I / \partial z = -\beta_3 I^3$ . For the numerical simulations we employed a (2D + 1) beam propagator with a standard Crank-Nicolson scheme and Gaussian spatio-temporal excitation, using  $n_2 = 5 \times 10^{-15} \text{ cm}^2 / \text{W}$  and  $\beta_3 = 4 \times 10^{-4} \text{ cm}^3 / \text{GW}^2$  as best fit values [29].

### 3. Self-trapped beams and their interaction

Self-trapped beams in a Kerr system with nonlinear absorption can propagate if excited by a power close to the material dependent critical value  $P_{CR} = \lambda^2 / 2\pi n_0 n_2$  [33]. For lower powers the beam diffracts, for higher powers it loses part of its energy through nonlinear absorption and then reshapes and diffracts into a Bessel-like beam [24]. Figure 1 shows typical output profiles of a single beam propagating in the HMO sample for various peak-power excitations corresponding to  $P < P_{CR}$ ,  $P \approx P_{CR}$  and  $P > P_{CR}$ , respectively.

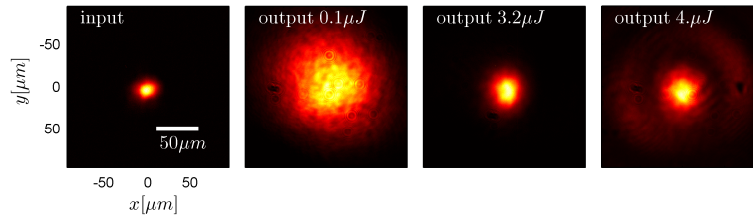


Fig. 1. Nonlinear beam propagation in a 5.75mm-long sample of HMO: input (leftmost photograph) and output beam profiles for input peak power  $P < P_{CR}$  (linear diffraction at 0.1 μJ, power  $P \approx P_{CR}$  (self-trapping at 3.2 μJ), power  $P > P_{CR}$  (beam reshaping at 4 μJ).

We observed soliton-like beam formation for excitations close to 3.2 μJ, corresponding to a peak power of 118 kW. The measured single beam transmission versus input energy, plotted in Fig. 2, pinpoints the presence of a 3PA process, in agreement with the model Eq. (1) and consistent with previous measurements in HMO [28,29]. Spatial solitons corresponded to losses not exceeding 20% (i.e. transmission  $\geq 80\%$ ).

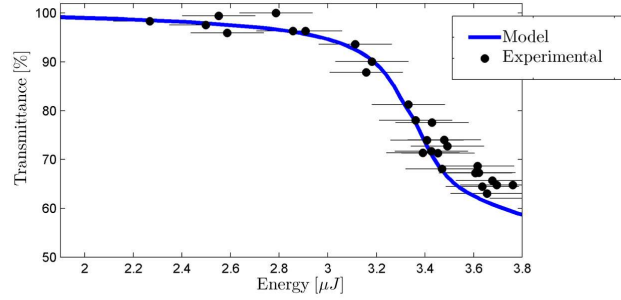


Fig. 2. HMO transmission versus input energy/pulse for a single beam excitation. Symbols and error bars refer to data and the solid line is a fit based on Eq. (1) and the parameters indicated in the text.

We investigated the interaction between two pulsed beams versus input pulse energy, initial separation and relative phase. The strength of the interaction was controlled by the separation and its nature by their relative phase. We show hereby our experimental results for an initial transverse distance of  $40\mu\text{m}$ . By controlling the relative phase, attraction or repulsion or energy transfer between the self-trapped beams could be observed.

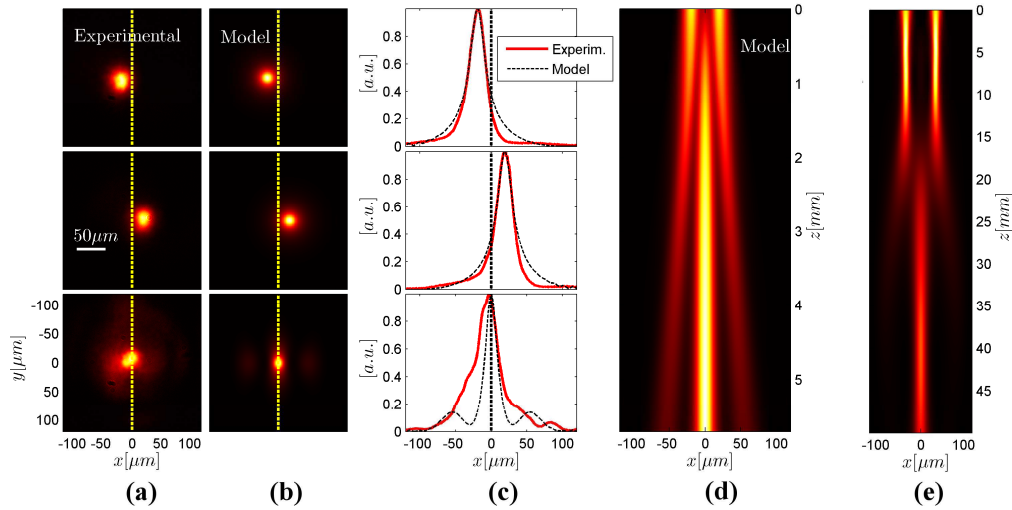


Fig. 3. Attraction of in-phase  $3.2\mu\text{J}$  self-trapped beams for a  $40\mu\text{m}$  initial separation. (a) CCD-acquired and (b) numerically simulated output profiles of individual (first two rows) and interacting solitons (bottom); (c) Corresponding measured and calculated transverse profiles along  $x$ ; (d) simulated evolution of the two solitons in the plane  $xz$ . (e) Simulated evolution of in-phase self-trapped beams for  $70\mu\text{m}$  initial separation,  $3.2\mu\text{J}$  excitation and propagation over  $5\text{cm}$ : the merging generates a single self trapped beam with no sidelobes.

When the solitons are in phase they attract each other, until they eventually coalesce: Fig. 3(a) displays the experimental results for  $P \approx P_{CR}$  along with the simulated behaviour in Fig. 3(b) according to Eq. (1). Figure 3(c) compares actual and simulated transverse profiles. During coalescence, the exceeding energy is radiated sideways around the solitons, as apparent in the numerical evolution displayed in Fig. 3(d) and in the data at the bottom of Fig. 3(a). At excitations higher than  $5\mu\text{J}$ , optical damage occurred near the output facet of the sample. Owing to the dissipative nature of the medium, an individual self-trapped beam can be obtained by properly choosing the interaction strength (i.e. the input separation) and the

propagation length, as shown by the simulation in Fig. 3(e) for the same excitation but a larger initial separation and a longer propagation length.

For an input relative phase of  $\pi$  the  $3.2\mu\text{J}/\text{pulse}$  solitons repel one another, as visible in Fig. 4: after 5.75mm the distance between the beams along  $x$  increases from 40 to  $80\mu\text{m}$ .

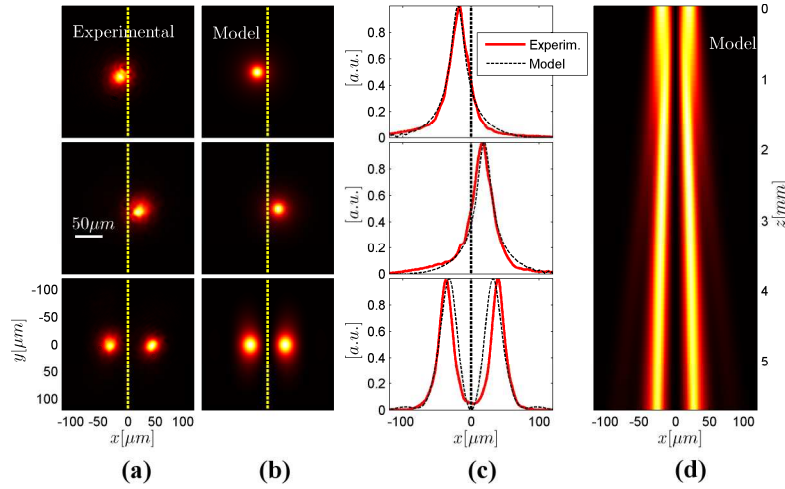


Fig. 4. Repulsion of  $\pi$  out-of-phase self-trapped beams excited by  $3.2\mu\text{J}$  pulses for  $40\mu\text{m}$  initial separation. (a) CCD-acquired and (b) numerically simulated output profiles of individual (first two rows) and interacting solitons (bottom); (c) Corresponding measured and calculated transverse profiles along  $x$ ; (d) simulated evolution of the two solitons in the plane  $xz$  of propagation.

The HMO transmission versus total input energy for two-beam excitations is plotted in Fig. 5 for both mutual attraction and repulsion, respectively. The nonlinear losses of two interacting beams of given input energy always exceed those of single (or non-interacting) beams of equal energy, as expected due to the coherent nature of the interaction and the nonlinear dependence of 3PA on the intensity. Even in the case of repulsion, the initial proximity of the launched beams causes 3PA to be larger than in the one beam case (Fig. 2).

For intermediate values of the relative phase, energy exchange between the solitons was observed. For the same initial separation and energy as in Fig. 3 and Fig. 4, at relative phases of  $\pi/2$  or  $3\pi/2$  the self-trapped beam which is phase-delayed with respect to the other spills and accumulates energy, eventually growing in intensity. Figure 6 shows experimental results in good agreement with the numerical simulations.

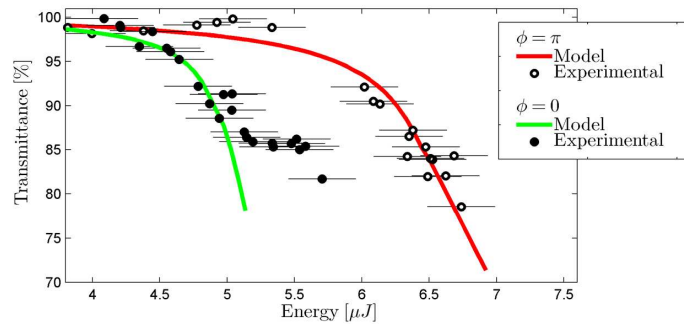


Fig. 5. HMO transmission versus input energy/pulse for two identical interacting beams with relative phase  $\phi = 0$  and  $\phi = \pi$ , respectively. Symbols are data and lines are fits based on Eq. (1).

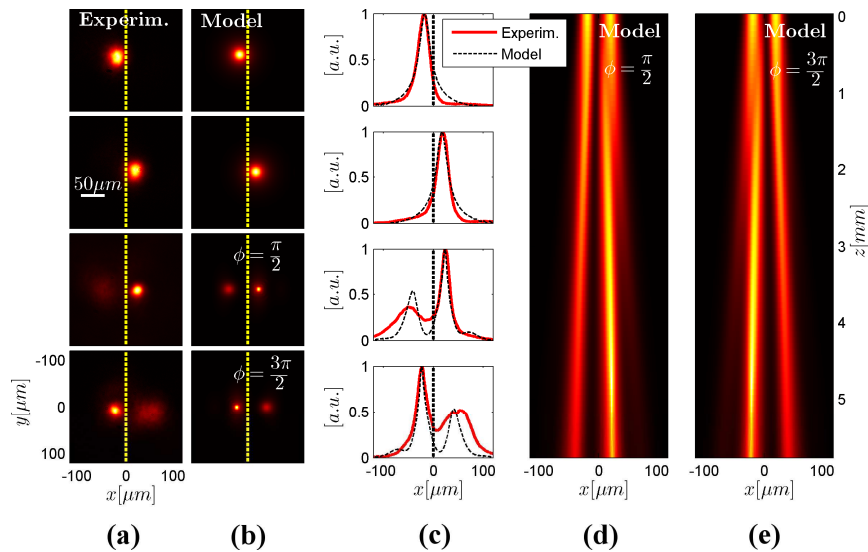


Fig. 6. Energy exchange between self-trapped beams excited by  $3.2\mu J$  pulses and launched in-quadrature with a  $40\mu m$  separation. (a) CCD-acquired and (b) numerically simulated output profiles of individual (first two rows) and interacting solitons out of phase by  $\pi/2$  (third row) or  $3\pi/2$  (last row); (c) Corresponding measured and calculated transverse profiles along  $x$ . Simulated evolution in the plane  $xz$  for solitons out of phase by (d)  $\pi/2$  and (e)  $3\pi/2$ .

#### 4. Conclusions

In conclusion, we investigated the nonlinear interaction of self-trapped beams in a heavy-metal-oxide glass of the ternary system  $Nb_2O_5$ - $GeO_2$ - $PbO$ , exciting solitons in the first window for fiber optical communications, i.e. in a spectral region where three-photon absorption provided transverse stabilization. We observed attraction, repulsion and energy exchange by controlling the relative phase of two coherent beams launched with a modest separation to allow their coherent interaction. The results, modeled with a nonlinear Schrödinger equation corrected for three-photon absorption, reveal the fingerprints of multiphoton losses with moderate propagation losses ( $\sim 20\%$ ), making this ultrafast glass system a good candidate for soliton based interconnects.

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